

Identifying mechanisms of quantum nematic transitions from the dynamic susceptibility

CORRELATED ELECTRON SYSTEMS – NOVEL DEVELOPMENTS
FTPI – MAY 2018

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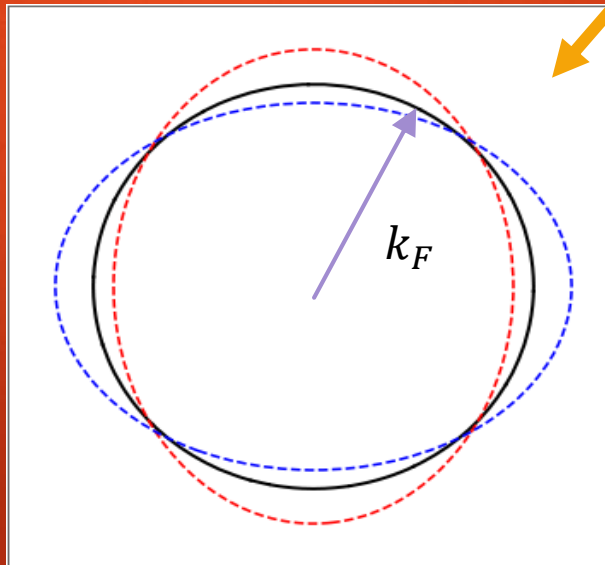
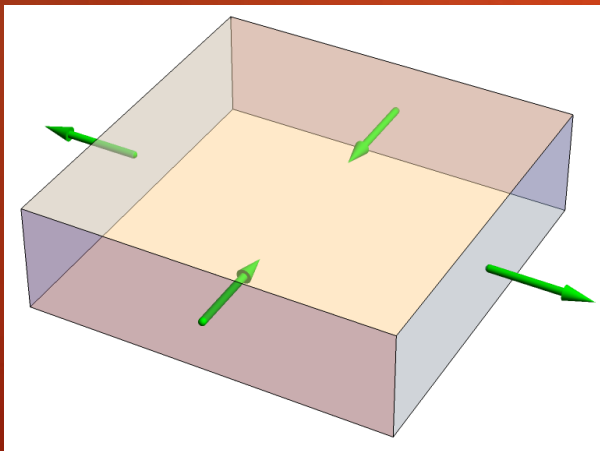


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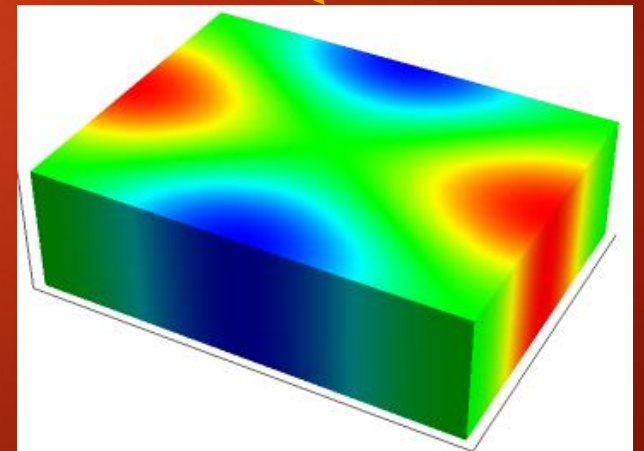
Background

- ▶ Electronic nematicity
 - ▶ Quadruple deformation
 - ▶ Elliptic Fermi surface



Long wavelength
 $Q = 0$

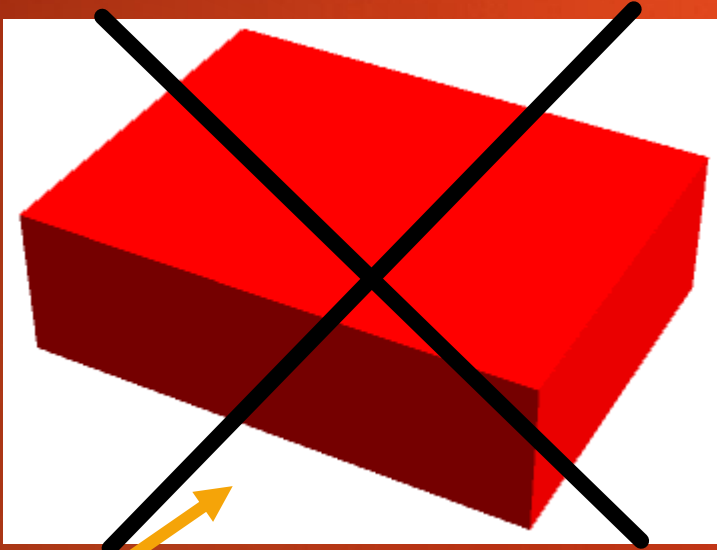
Anisotropic



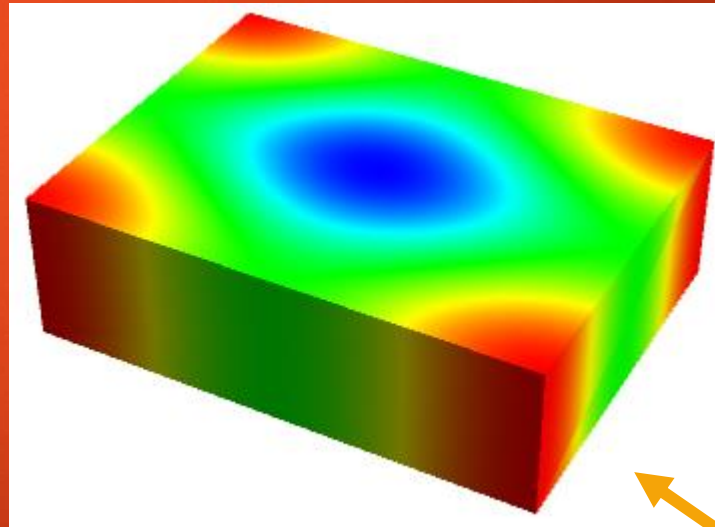
Background

- ▶ Interacting electrons have two distinct regimes:

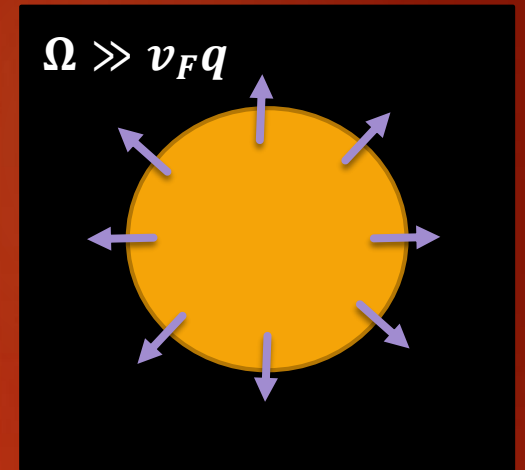
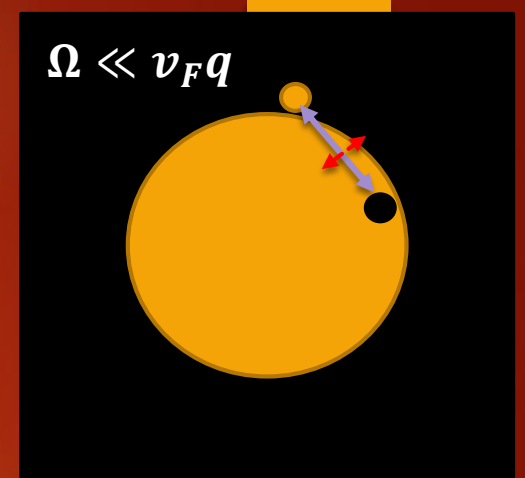
$$v_F q \gg \Omega \text{ and } v_F q \ll \Omega$$



Conserved order
parameter



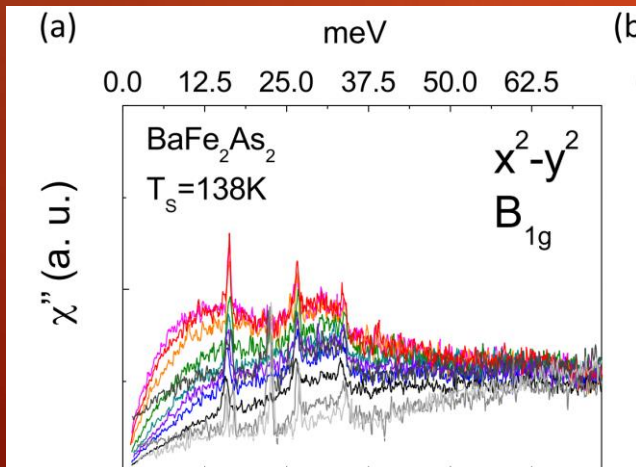
New regime to study!



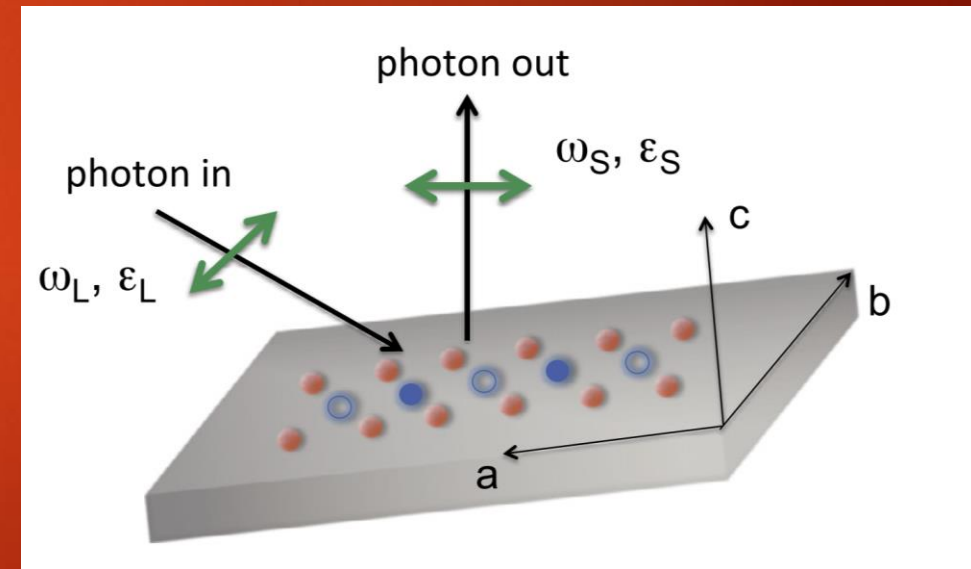
Nonconserved
order parameter

Background

- ▶ Polarization resolved Raman scattering
 - ▶ Strongly correlated materials (Fe-based superconductors)
- ▶ Optical measurement: $\Omega \gg v_F q$
 - ▶ Measures electronic density fluctuations:

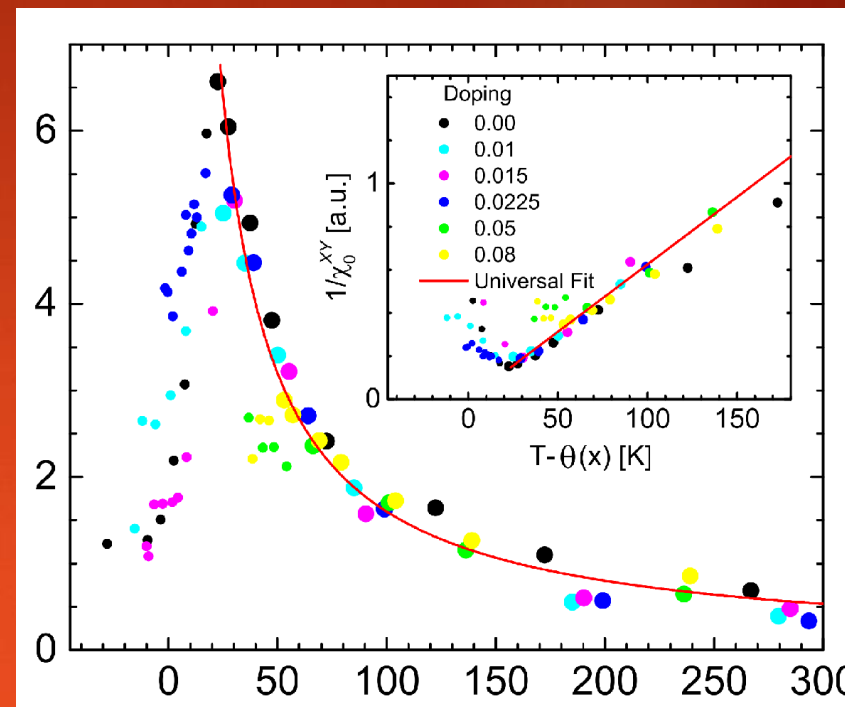


$$I(\Omega) \propto \chi''_{l=2}(\Omega)$$



Background

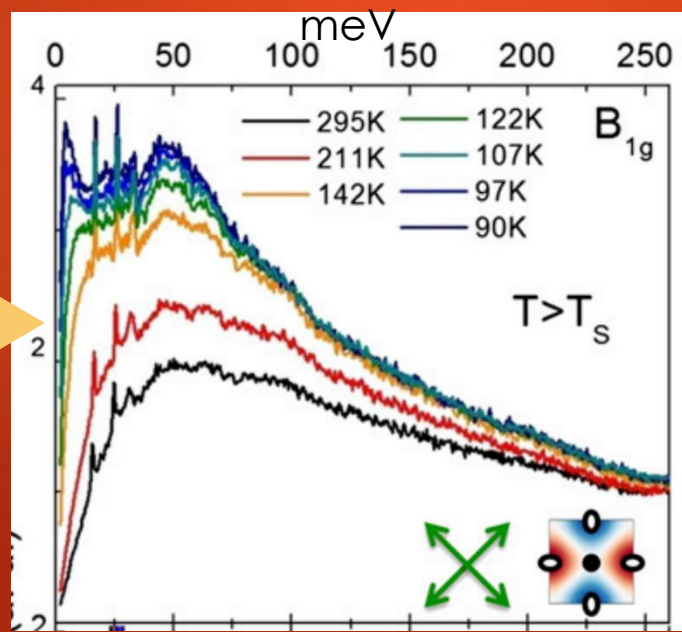
- ▶ Raman studies of $\text{FeSe}_{1-x}\text{S}_x$
- ▶ Many other materials as well



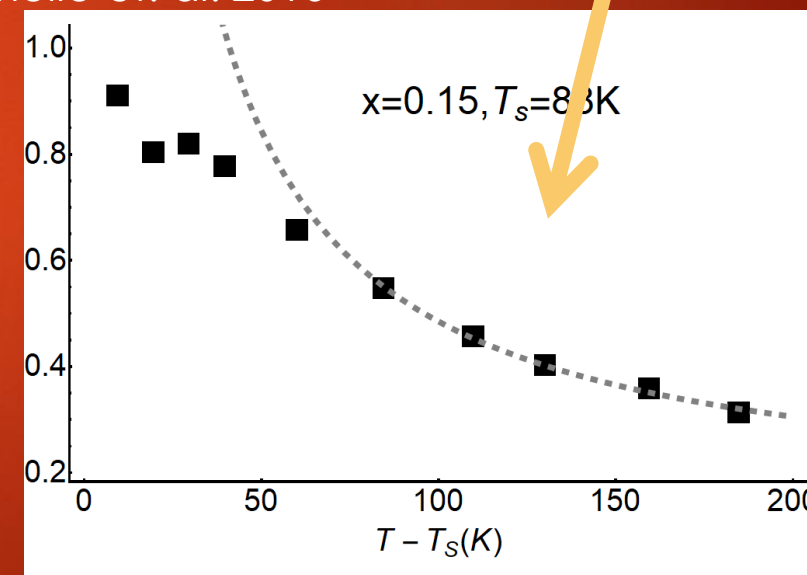
V Thorsmølle et. al. 2016

$\chi'(0)$

$\chi''(\Omega)$



P Massat et. al. 2016



W.-L. Zhang et. al. (private/2017)

Outline

Model and
central
results

$\text{FeSe}_{1-x}\text{S}_x$
Raman
highlights

Theory
highlights

Summary

Model

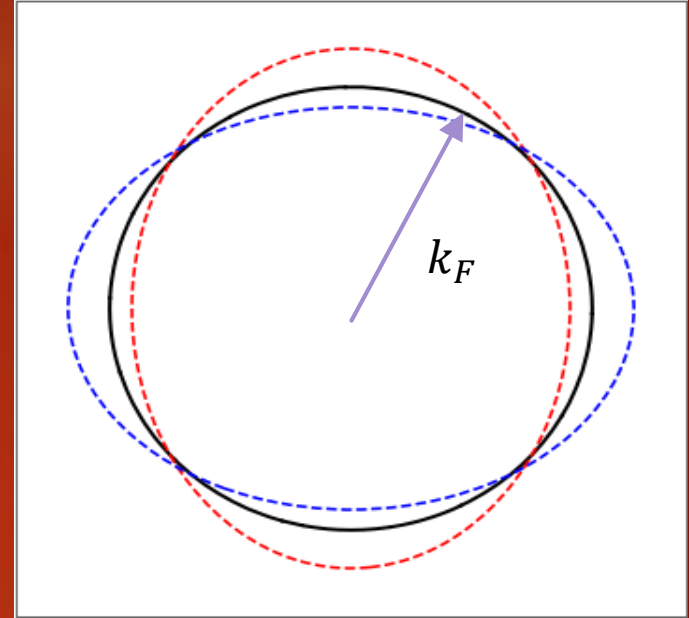
- ▶ 2D fermions + nematic boson
- ▶ Hamiltonian:

$$H_I = g \sum_{\mathbf{k}, \mathbf{q}} \phi(\mathbf{q}) \psi^\dagger \left(\mathbf{k} + \frac{\mathbf{q}}{2} \right) \psi \left(\mathbf{k} - \frac{\mathbf{q}}{2} \right) f(\mathbf{k})$$

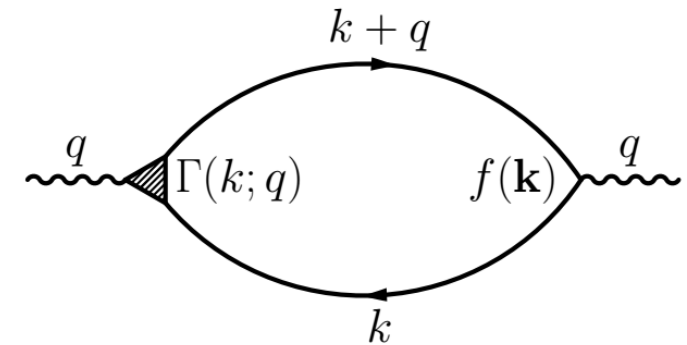
$$f(k) \approx f(\phi_k) = \cos(2\phi_k)$$

- ▶ Boson critical dynamics:

$$\chi(\mathbf{q}, \Omega_m \ll v_F q) = \frac{\chi_0}{\xi^{-2} + q^2 + \gamma \frac{|\Omega_m|}{v_F q} f^2(\phi_q)}$$



OUR GOAL

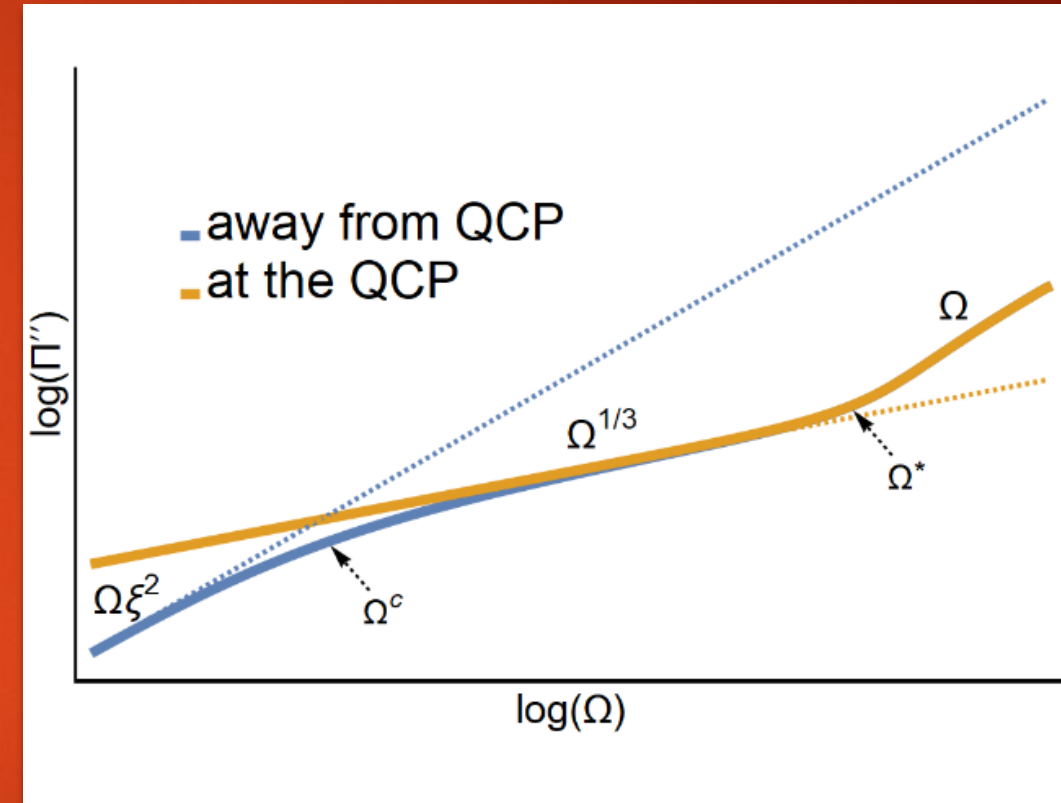
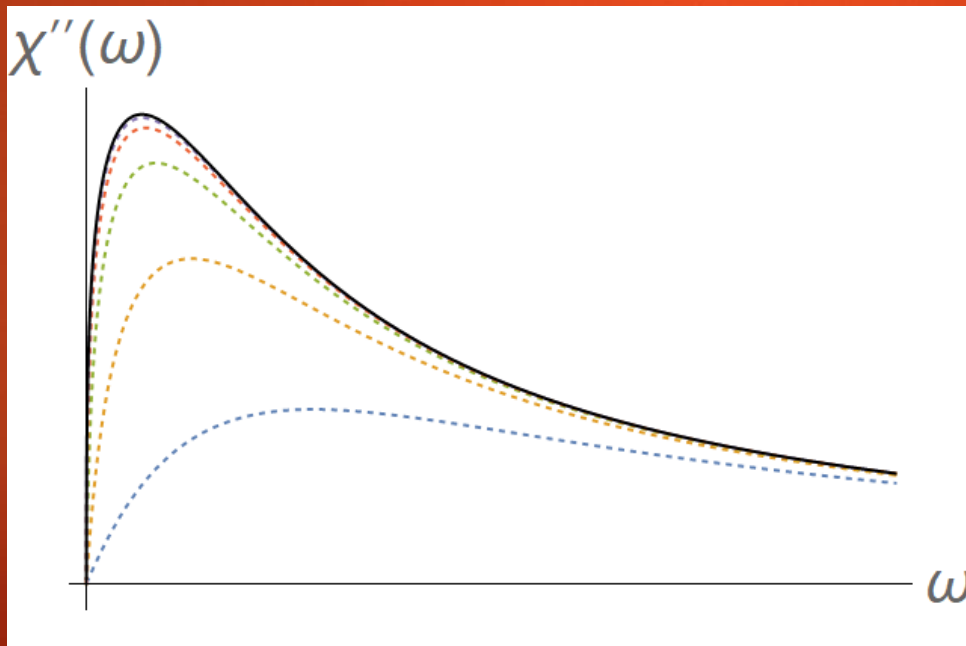


$\Pi(\mathbf{q} = 0, \Omega_m)$

Results

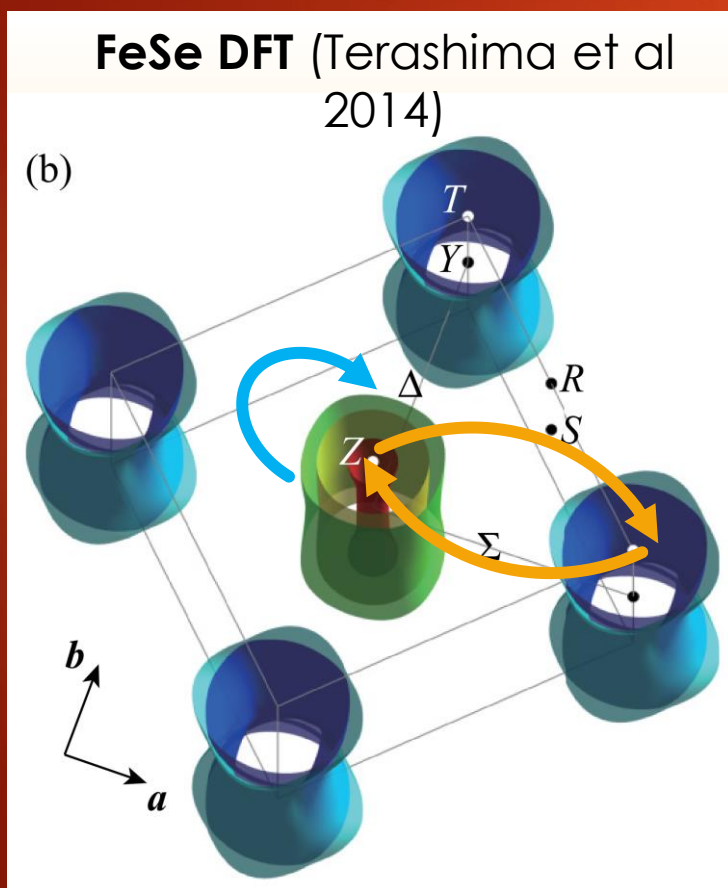
► Result #1: form of $\Pi(q = 0, \Omega)$:

► $\Pi(\Omega_m) \sim \Pi_0(\xi^{-1}) + \begin{cases} \Omega_m \xi^2 & \Omega \ll \Omega^c \sim \xi^{-3} \\ \Omega_m^{1/3} & \Omega \gg \Omega^c \end{cases}$



Results

► Result #2: identifying mechanisms of nematicity



Pomeranchuk	Independent
Orbital (charge)	Composite magnetism
	Phonons
	...

Results

- Result #2: identifying mechanisms of nematicity

	Pomeranchuk	Independent
Critical scales	ξ	ξ_0, ξ
Amplitude $\chi(q \rightarrow 0, \Omega = 0)$	$\chi_0 \xi^2$	$\chi_0 \xi^2$
Amplitude $\chi(q = 0, \Omega \rightarrow 0)$	Π_0	$\chi_0 \xi_0^2$
Slope $\chi''(\Omega)/\Omega$	$\propto \xi^2$	$\propto \xi^2 \xi_0^4$

Results

- Result #2: identifying mechanisms of nematicity

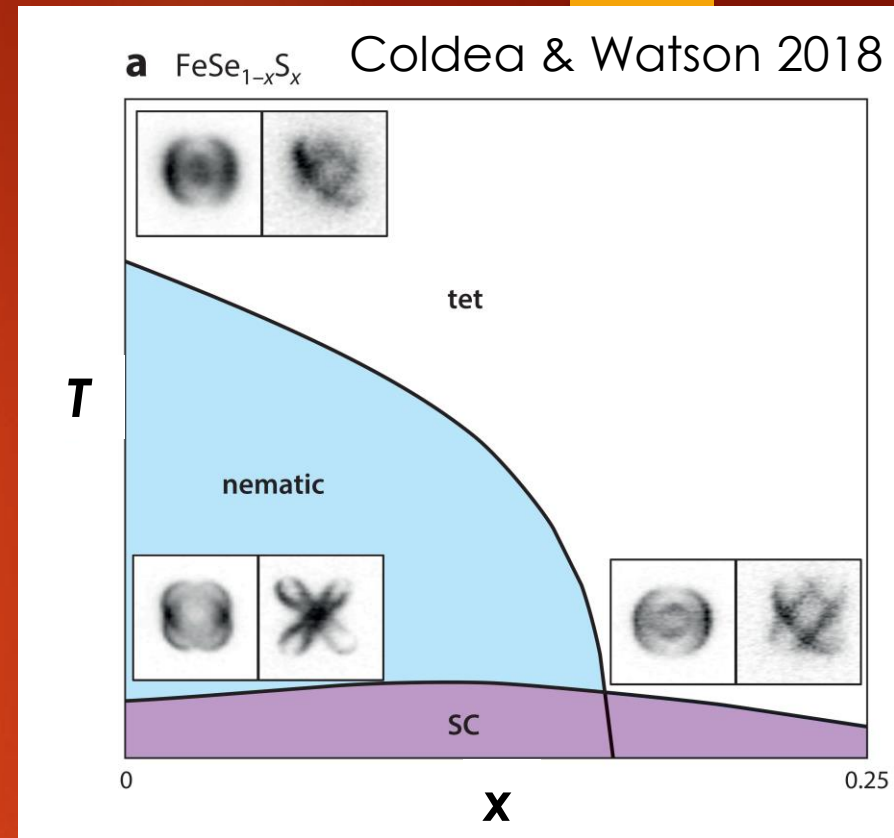
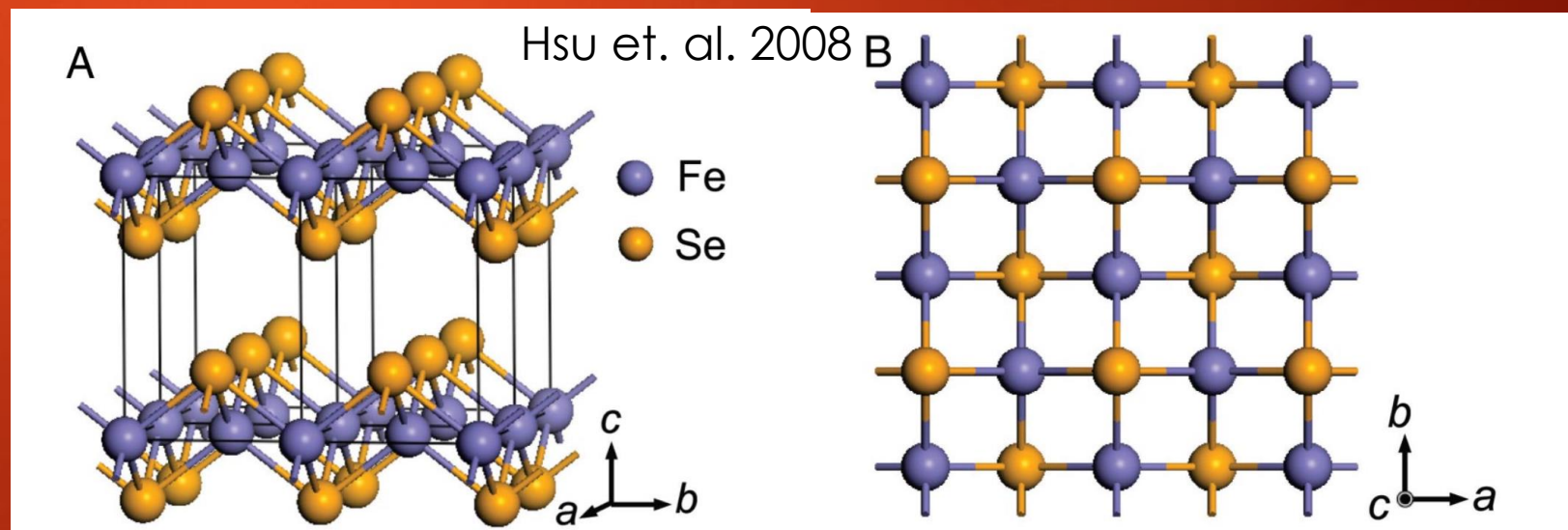
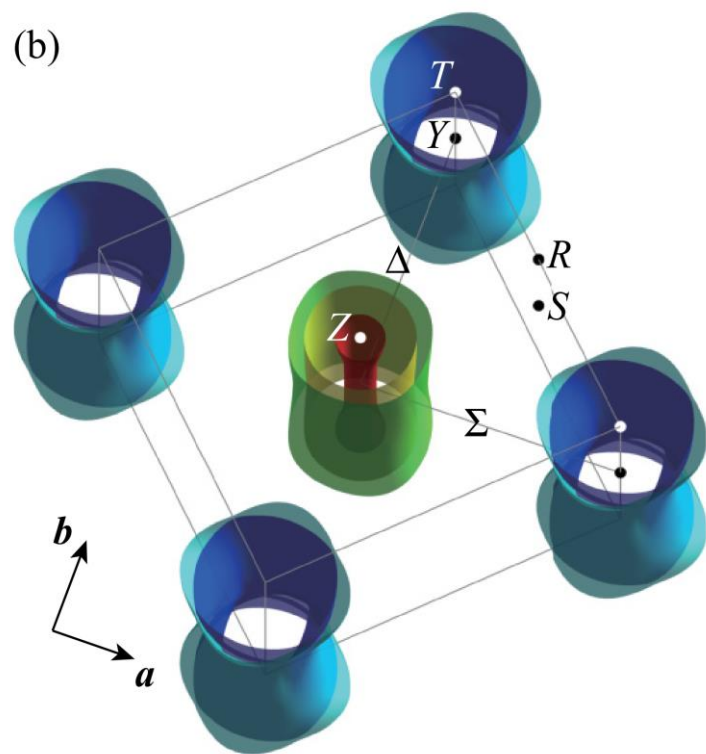
Pomeranchuk	Independent
$\chi_{pom} = \frac{\Pi}{1 - \bar{g}\Pi}$	$\chi_{ind} = \frac{\chi_0}{\xi_0^{-2} - \bar{g}'\Pi}$
$\xi^{-2} = \xi^{-2}$	$\xi^{-2} = \xi_0^{-2} - \bar{g}'\Pi_0$

Large for $\Omega \ll v_F q$ only!

$\text{FeSe}_{1-x}\text{S}_x$ analysis highlights

► Some background on FeSe:

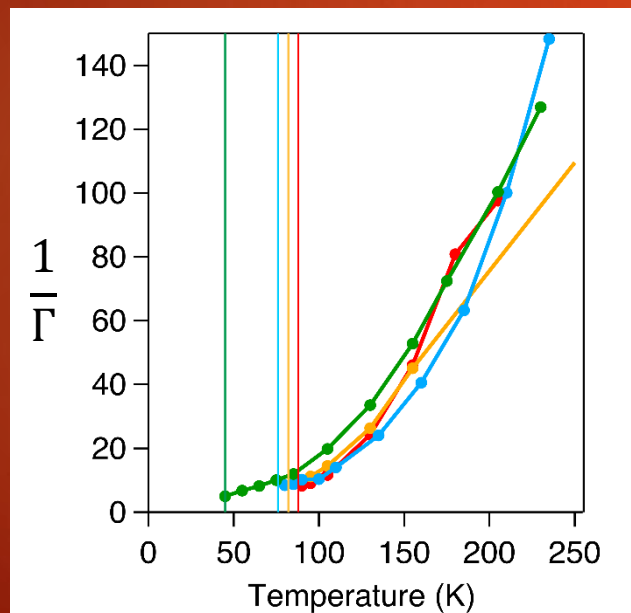
DFT (Terashima et al 2014)



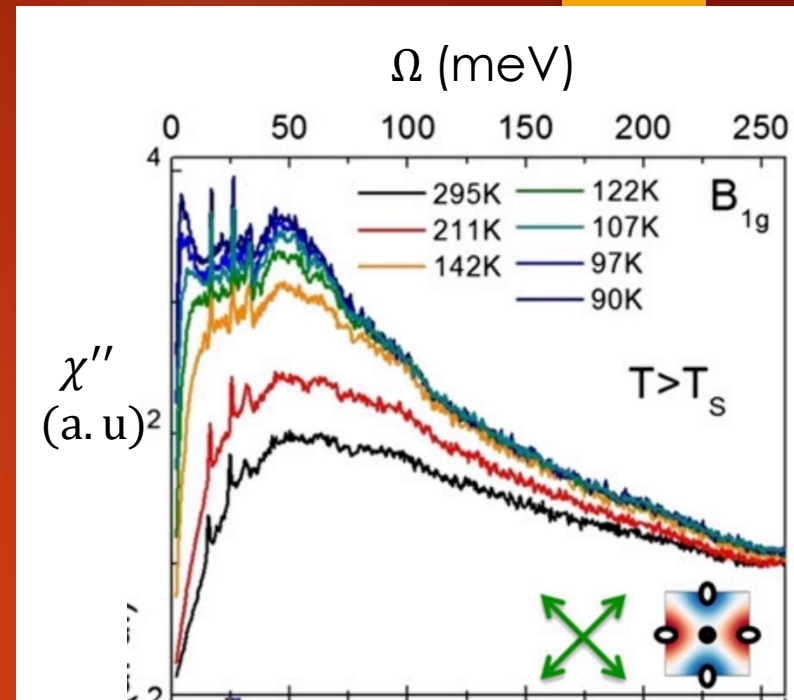
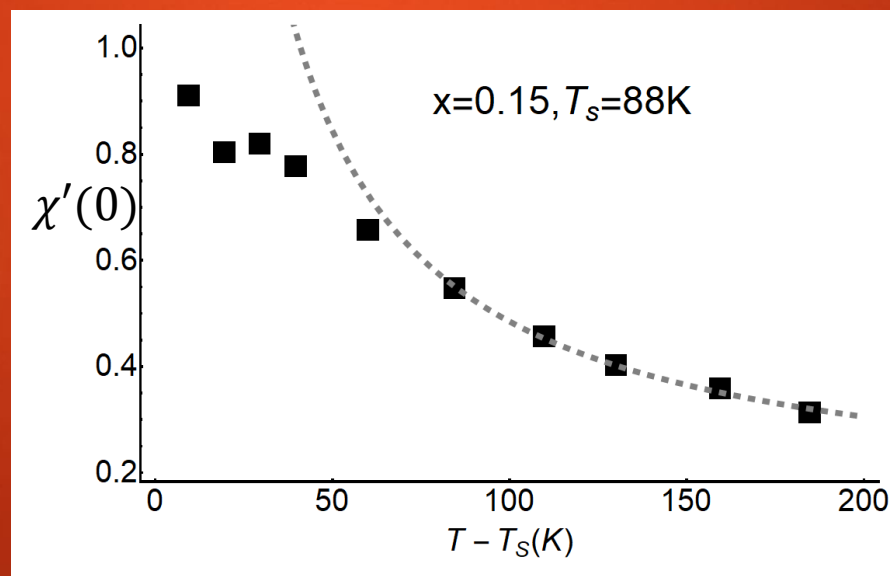
FeSe_{1-x}S_x analysis highlights

► Raman studies on FeSe_{1-x}S_x:

- Slope: $\Gamma = \chi''(\Omega \rightarrow 0)/\Omega$
- Amplitude: $\chi'(0) \sim \int \frac{\chi''(\Omega)}{\Omega} d\Omega$



W.-L. Zhang et. al. (private/2017)



P Massat et. al. 2016

FeSe_{1-x}S_x analysis highlights

- Comparison with theory (Pomeranchuk):

$$\chi'(0) = \Pi_0 \left(1 - \frac{\arctan(k_F \xi)}{k_F \xi} \right) = \Pi_0 \left(1 - \frac{\pi}{2k_F \xi} + \dots \right)$$

$$\delta\chi' = \chi'_{\xi \rightarrow \infty}(0) - \chi'_\xi(0) \propto \xi^{-1}$$

$$\Gamma = \frac{\chi''(\Omega \rightarrow 0)}{\Omega} \propto \xi^2$$

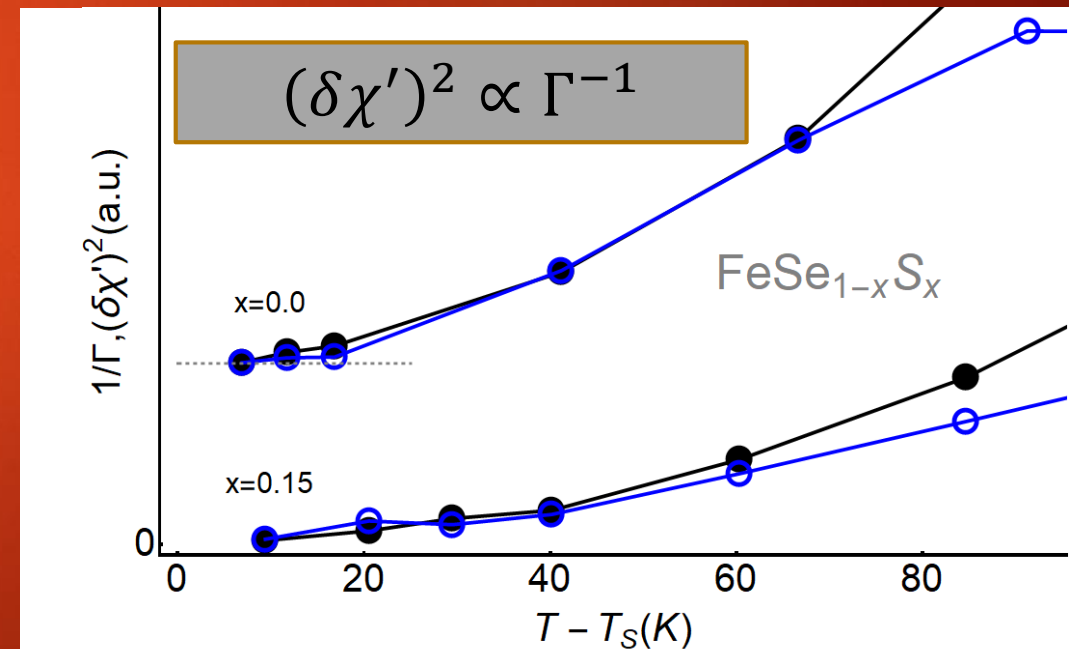
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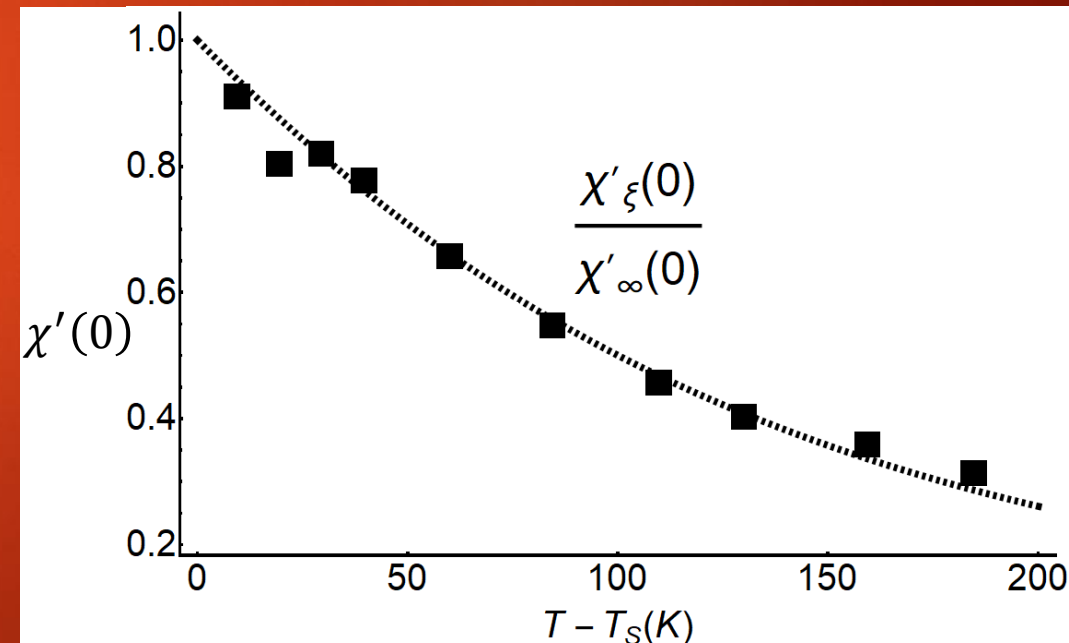
FeSe_{1-x}S_x analysis highlights

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$$\delta\chi' = \chi'_{\xi \rightarrow \infty}(0) - \chi'_{\xi}(0) \propto \xi^{-1}$$

$$\Gamma = \frac{\chi''(\Omega \rightarrow 0)}{\Omega} \propto \xi^2$$



What about pnictides?

Other theories, e.g.:
Y Gallais, I Paul 2016
A Baum et. al. 2018
M Khodas, A Levchenko 2015

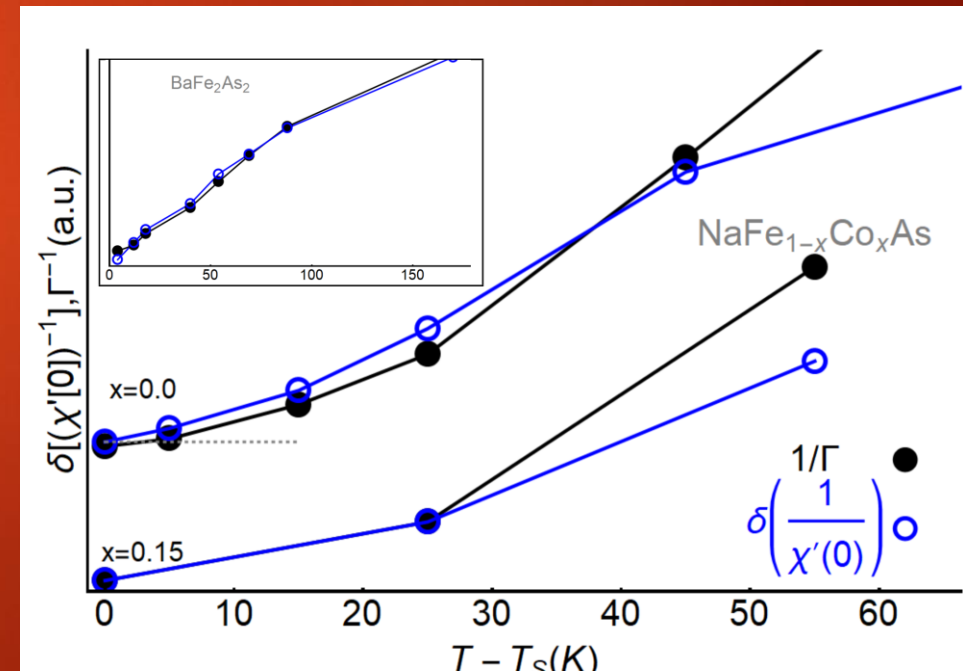
- 'Independent' scenario:

$$\delta\chi' \propto \xi^{-2}\xi_0^2 \quad \delta\left(\frac{1}{\chi'}\right) \propto \xi^{-2}$$

$$\Gamma^{-1} \propto \xi^{-2}\xi_0^{-4}$$

- Assuming constant ξ_0 ,

$$\delta\chi' \sim \delta\left(\frac{1}{\chi'}\right) \sim \Gamma^{-1}$$



Theory highlights

► Reminder:

- Fermions coupled to QC boson

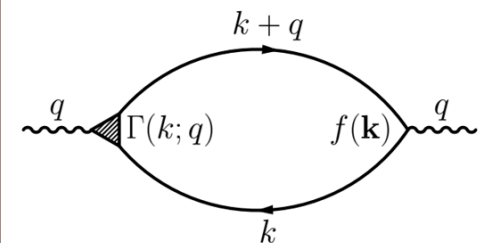
$$H_I = g \sum_{\mathbf{k}, \mathbf{q}} \phi(\mathbf{q}) \psi^+ \left(\mathbf{k} + \frac{\mathbf{q}}{2} \right) \psi \left(\mathbf{k} - \frac{\mathbf{q}}{2} \right) f(\mathbf{k})$$
$$f(k) \approx f(\phi_k) = \cos(2\phi_k)$$

► Energy scales (at QCP):

Onset of Landau Damping (critical boson)	Onset of NFL (critical fermion)
$\omega_1 \propto \sqrt{\bar{g} \epsilon_F}$	$\omega_0 \propto \frac{\bar{g}^2}{\epsilon_F}$

$$\omega_0 \ll \omega_1$$

OUR GOAL

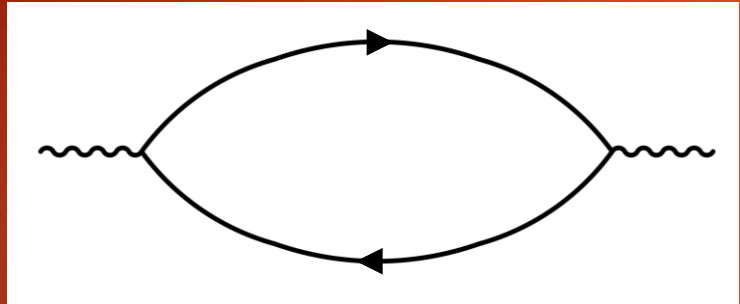


$$\Pi(\mathbf{q} = 0, \Omega_m)$$

Altshuler, Ioffe, Millis; ...

Theory highlights

- ▶ Free fermion susceptibility:



A Feynman diagram representing a fermion loop. It consists of two curved lines forming a closed loop, with arrows indicating a clockwise flow of fermions. Two wavy lines, representing external fields, are attached to the left and right vertices of the loop. The diagram is enclosed in a white rectangular box.

$$= 0$$

Free fermions \Leftrightarrow all k – states are conserved!

Theory highlights

► Next order ($\omega_0 \ll \Omega \ll \omega_1$):

The diagram illustrates the next-order correction to a bubble diagram in the NFL regime. It shows the sum of three diagrams on the left equaling a single diagram on the right. The first two diagrams on the left are bubble diagrams with a wavy line (representing a photon) attached to the top and bottom arcs. The third diagram on the left is a bubble diagram with a vertical wavy line (representing a photon) connecting the two vertices. The right-hand side is a bubble diagram with a vertical wavy line connecting the two vertices, labeled with the expression $f(\mathbf{k} + \mathbf{p}) - f(\mathbf{k})$ in pink.

$$\text{Bubble with top wavy line} + \text{Bubble with bottom wavy line} + \text{Bubble with vertical wavy line} = \text{Bubble with vertical wavy line labeled } f(\mathbf{k} + \mathbf{p}) - f(\mathbf{k})$$

Breaks down for $\Omega < \omega_0$ (NFL regime)

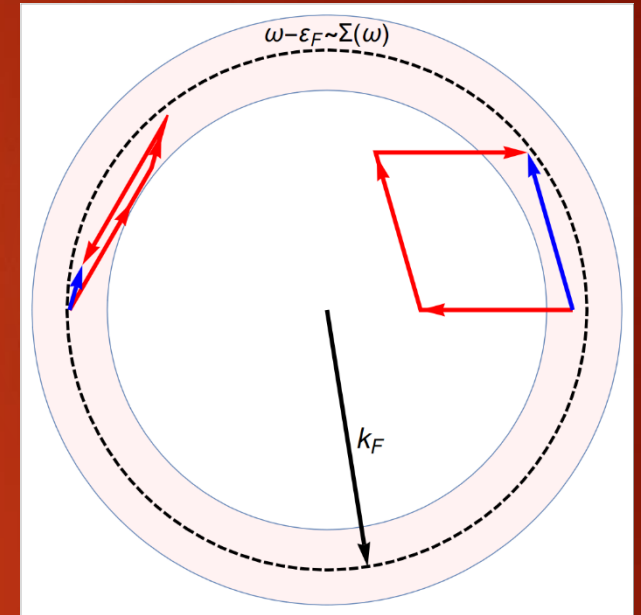
Theory highlights

- ▶ Eliashberg theory ($\Omega_m \ll \omega_0$):
 - ▶ Most singular contributions:

$$\chi_{eff}(\Omega_m) \sim \frac{1}{q} \sim \frac{1}{\Omega_m^{1/3}}$$

$$q \sim \Omega_m^{\frac{1}{3}} \ll k_F$$

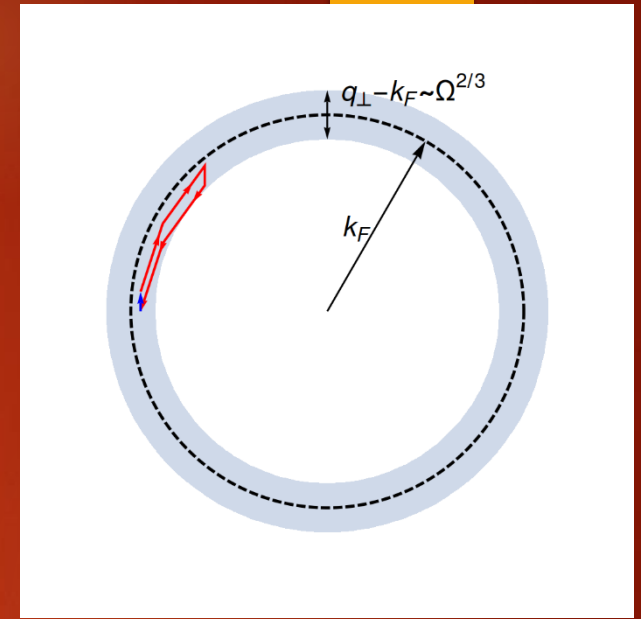
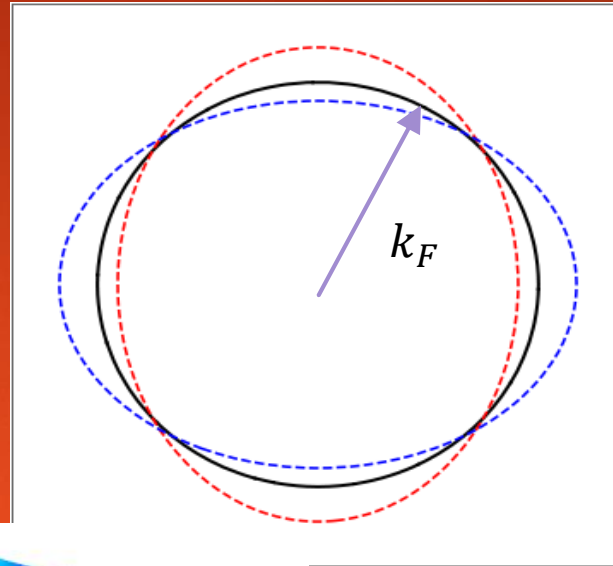
$$\Sigma(\omega_m) \sim \omega_m^{\frac{2}{3}} \ll q$$



$$\chi = \frac{\chi_0}{q^2 + \gamma \frac{|\Omega_m|}{v_F q} f^2(\phi_q)}$$

Theory highlights

- Eliashberg theory ($\Omega_m \ll \omega_0$):
- Most singular contributions:



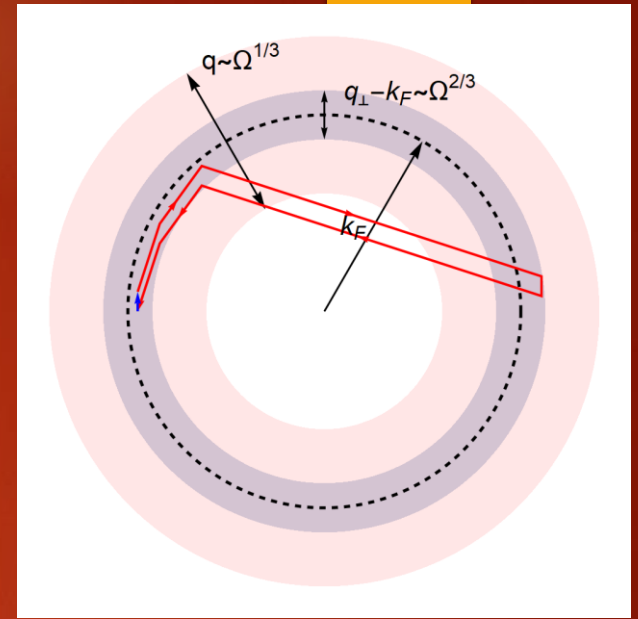
A series of Feynman diagrams and a 3D surface plot. On the left, a bubble diagram with wavy external lines. In the middle, a 3D surface plot showing a saddle-like shape with a color gradient from blue (low) to red (high). On the right, a bubble diagram with two internal wavy lines, followed by an ellipsis. The entire expression is set equal to zero.

$$= 0$$

Small $q \sim 0$ – still conservation law!

Theory highlights

- Eliashberg theory ($\Omega_m \ll \omega_0$):
 - Most singular contributions:



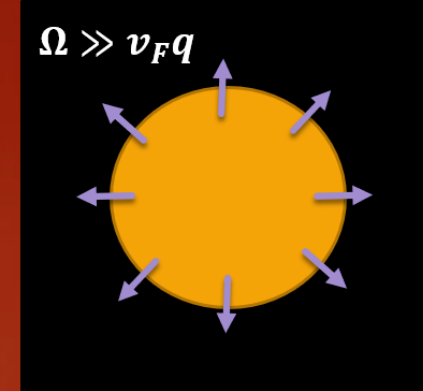
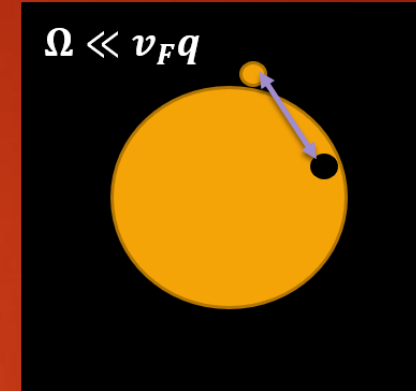
A series of Feynman diagrams representing a sum of bubble diagrams. The first diagram is a simple bubble with two external wavy lines. The second diagram has one internal wavy line. The third diagram has two internal wavy lines. The series continues with an ellipsis, followed by an equals sign and a large zero, indicating that the sum is zero.

- Large k correction:

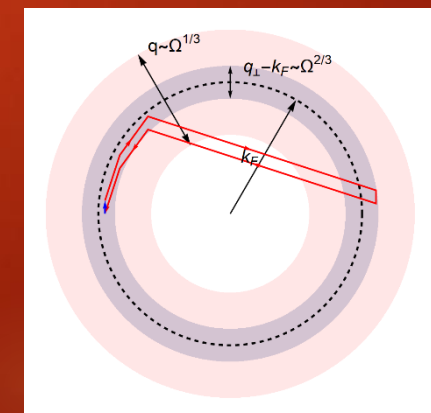
A series of Feynman diagrams showing a correction to the bubble diagram series. The first diagram is a bubble with one internal wavy line. An arrow points to a second diagram where the bubble is shaded and has a red line segment. This is followed by an equals sign, an ellipsis, a third diagram where the bubble is shaded and has multiple red wavy lines, and another ellipsis, indicating a series of corrections.

Summary

- ▶ Nonconserved order parameter
 - ▶ 'new' regime to study: $\Omega > 0, q = 0$
- ▶ Can identify driving mechanism
 - ▶ $\delta\chi' \sim \Gamma^{-1}$ vs $\delta\chi'^2 \sim \Gamma^{-1}$
 - ▶ FeSe – good agreement with Pomeranchuk scenario
- ▶ Interplay between conservation laws and strong fluctuations
 - ▶ Singular fluctuations interfere destructively
 - ▶ No divergences: $\chi'' \propto \xi^2 \Omega, \Omega^{\frac{1}{3}}$



Pomeranchuk	Independent
ξ	ξ_0, ξ





Thank you!